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Cost and Performance Report

(MM-0414)

Man-Portable Simultaneous Magnetometer and EM System (MSEMS)

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ACRONYMS AND ABBREVIATIONS

APG	Aberdeen Proving Grounds
ASIC	application-specific integrated circuit
CEHNC	U.S. Army Corps of Engineers Engineering and Support Center, Huntsville
COTS	commercial off-the-shelf
CRADA	Cooperative Research and Development Agreement
DGM	digital geophysical mapping
EM	electromagnetic
EOD	explosive ordnance disposal
EPROM	erasable programmable read-only memory
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
GIS	geographic information system
GPO	geophysical prove-out
GPS	Global Positioning System
GUI	graphical user interface
HD	Humanitarian Demining
HTRW	hazardous toxic radioactive waste
IPR	Interim Program Review
ITRC	Interstate Technology and Regulatory Council
MEC	munitions and explosives of concern
MPC	magnetometer period counter
MPI	man-portable interleaving
ms	millisecond
MSEMS	Man-Portable Simultaneous Electromagnetic Induction and Magnetometer System
mV	millivolts
NAOC	National Association of OEW Contractors
NRE	non-recurring engineering
nT	nanotesla
NVESD	(U.S. Army's) Night Vision and Electronic Sensors Directorate
OEW	ordnance and explosive waste
PDA	personal digital assistant
PI	principal investigator
pps	pulse per second

ACRONYMS AND ABBREVIATIONS (continued)

PSYNC	Synchronization Pulse
RTK	real-time kinematic
SAIC	Science Applications International Corporation
SCEMP	Simplified Combined EMI and Magnetometer System
SNR	signal-to-noise ratio
TSEMS	Towed Simultaneous Electromagnetic Induction and Magnetometer System
μs	microseconds
USEMS	Underwater Simultaneous EMI and Magnetometer System
UXO	unexploded ordnance
VSEMS	Vehicular Simultaneous EMI and Magnetometer System
YPG	Yuma Proving Grounds

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Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

Pulsed induction sensors (particularly the Geonics EM61 Mk2) and total field magnetometers are the two primary sensors employed for detection of munitions and explosives of concern (MEC) on formerly used military properties. While these two sensors have a broadly overlapping performance envelope, each sensor has unique strengths. The EM61 is the better sensor for detection of small and/or nonferrous projectiles, while the magnetometer excels at detection of large, deep objects. Unfortunately, codeployment of the two sensors is normally impossible due to the active nature of pulsed electromagnetic (EM), which creates noise on any nearby magnetometer. A prior Environmental Security Technology Certification Program (ESTCP) project (MM-0208) developed the technology needed to codeploy these two sensors through the process of interleaving (sampling the magnetometer only between the EM61's pulses when the EM61 is quiet) and deployed that technology on a vehicular platform. Under this project, a Man-Portable Simultaneous Electromagnetic Induction (EMI) and Magnetometer System (MSEMS) was developed. The interleaving hardware was made smaller and lighter to enable man-portable deployment. A box with standard interfaces was developed that allows any geophysical contractor with EM61s, total field magnetometers, and Global Positioning System (GPS) equipment in inventory to connect them to our interleaving hardware and collect high-quality, concurrent mag/EM61 data. Two physical configurations were developed using this hardware: 1) a configuration with an unmodified EM61 and the magnetometer four feet in front of the EM61 coil and 2) a configuration using an EM61, whose pulse repetition rate was slowed to allow the magnetometer to acquire interleaved data when placed in the middle of the EM61 coil. The system was demonstrated at Yuma Proving Grounds (YPG), Arizona. The objectives of the demonstration were 1) to validate that the new smaller, lighter interleaving electronics worked as designed; 2) to determine whether the MSEMS system constructed around that new hardware was usable for real-world Digital Geophysical Mapping (DGM); and 3) to determine which of the two physical configurations was best. Both objectives were met. The "mag-in-the-middle" configuration proved to have unacceptably low signal to noise, but the version using the unmodified EM61 concurrently collected high-quality EM61 and magnetometer data like the vehicular technology previously validated under MM-0208. This configuration has since been used on several government and commercial MEC and hazardous toxic radioactive waste (HTRW) surveys. A patent has been granted for the method and apparatus of interleaving magnetometer data between EM61 pulses. The box containing the interleaving hardware is the basis for the mag/EM data acquisition hardware in another ESTCP project. There is serious commercial interest from three firms in purchasing an interleaving box.

2.0 INTRODUCTION

Under this project, hardware was developed that allows total field magnetometers and Geonics EM61 sensors—the two sensors most frequently deployed against MEC and accepted by regulators for cleanup of formerly used defense sites in this country—to be deployed together on a man-portable platform.

2.1 BACKGROUND

The technology demonstration exercises at Jefferson Proving Ground in the mid-1990s yielded the broad conclusion that metal detectors—specifically, total field magnetometers and pulsed induction sensors—were the most effective sensors against a range of MEC. The recent Interstate Technology and Regulatory Council (ITRC) Report[1] reiterated that conclusion, calling out the Geonics EM61 Mk2 pulsed induction sensor and the total field magnetometer (manufactured by Geometrics and other companies) as being the two most deployed and most effective sensors. Each of these sensors has its own strengths and weaknesses. Total field magnetometers, due to their $1/R^3$ response (where R is the distance between the source and the sensor) and their exquisite sensitivity, are the sensors of choice for detection of major caliber air-dropped munitions such as 250-lb bombs, provided the site geology does not contain iron-bearing soils. However, the very sensitivity that allows magnetometers to detect object to great depths also makes them susceptible to fields from cultural objects such as buildings and cars. Pulsed induction sensors are less responsive as a function of depth than magnetometers (the $1/R^3$ response comes into play for the outgoing pulse as well as the detected field, resulting in a depth response of $1/R^6$), but because they detect all metals, they outperform magnetometers for the detection of small objects such as 20 mm and 40 mm projectiles that have little or no ferrous content. In addition, because the field generated by a transmit coil is greatest directly beneath the coil, a pulsed induction sensor is less sensitive to anthropogenic clutter such as buildings and cars than a magnetometer. Ideally the two sensors should be deployed together, but the pulsed induction sensor is an active sensor whose electronics ramps up a current and then abruptly switches it off to generate the transmit pulse. This is a textbook example of a rapidly changing electric field that, according to Maxwell's equations, generates a magnetic field. For this reason, EM61s cannot be deployed within approximately 30 ft of a nearby magnetometer. Attempting to codeploy the two sensors on a common platform results in ruinous levels of noise in the magnetometer data. Thus, use of both sensors at a site necessitates two separate surveys, with its consequent cost.

Under a prior project (MM-0208), ESTCP funded U.S. Army Corps of Engineers Engineering and Support Center, Huntsville (CEHNC) and GEO-CENTERS (now Science Applications International Corporation [SAIC]) to develop electronics to concurrently acquire EM61 and total field magnetometer data through the technical approach of interleaving—monitoring the EM61's synchronization signal and only sampling the magnetometers during the short interval when the EM61 and all the secondary fields it generates are quiet. Project MM-0208 was successful and resulted in the Vehicular Simultaneous EMI and Magnetometer System (VSEMS), the world's only concurrent mag/EM61 vehicle towed array.

[1] SERDP ESTCP ITRC Survey of Munitions Response Technologies, June 2006

The goal of this project was to take the basic interleaving technology designed and demonstrated under MM-0208 and redesign it to enable man-portable application. This involved:

- Conducting a trade-off study to determine the closest distance a total field magnetometer can be reliably operated near an unmodified EM61
- Altering the timing parameters of the EM61 to ascertain if a magnetometer can be placed in the middle of the EM61 coil and still collect high-quality data
- Redesigning the boards in the interleaving hardware to make them smaller and lighter
- Building a man-portable interleaving (MPI) box with standard interfaces that allowed use of existing sensors and cables already in inventory, and of a form factor that allowed easy mounting with the other commercial off-the-shelf (COTS) EM61 equipment
- Constructing a system of our own, built around the MPI box, to enable us to demonstrate the new hardware.

2.2 OBJECTIVES OF THE DEMONSTRATION

The stated objectives of the demonstration as listed in the YPG Demonstration Plan were:

- To test the new prototype MSEMS hardware, software, and platform in a controlled environment and demonstrate that the MSEMS can withstand the rigors of real deployment
- To acquire magnetometer-only survey data as a baseline to compare with the concurrent EM and magnetometer survey data
- To acquire EM-only survey data as a baseline to compare with the concurrent EM and magnetometer survey data
- To acquire concurrent magnetometer and EM survey data from each of two configurations in order to be able to judge the quality of the data and the efficacy of the system design. The two configurations are:
    - Sensors physically separated by roughly four feet using an unmodified EM61 operating at 75 Hz
    - Sensors spatially colocated with the magnetometer in the middle of the EM61 coil and the EM61 slowed down to 15 Hz.

The system was demonstrated at YPG the week of 6/12/2006. All of the above objectives were met. The results of the demonstration were:

- The system functioned well, with only minor cabling and software glitches, which are expected of prototype hardware deployment.

- The 75 Hz mag-in-front configuration collected high-quality concurrent magnetometer and EM61 data, with no discernible difference between single-sensor data and concurrently acquired data.
- The 75 Hz mag-in-front configuration, with its “cart” design and third wheel, proved to be quite usable (the deployment produced a list of desired incremental improvements, all of which have since been made).
- The magnetometer can be left vertical when using the 75 Hz mag-in-front configuration, simplifying deployment logistics.
- The 15 Hz mag-in-the-middle configuration functioned as designed, collecting high-quality magnetometer data when the magnetometer was properly oriented for each survey line.
- There was no discernible difference between single-sensor magnetometer data and concurrently acquired magnetometer data.
- However, the factor-of-five loss in EM61 signal when operating at 15 Hz as compared to 75 Hz is very real, particularly over small weak objects, making the mag-in-the-middle configuration of questionable use for real-world DGM over anything except very strong objects.

2.3 REGULATORY DRIVERS

The primary driver is the continued need to develop tools to detect MEC. MSEMS will extend the benefits of VSEMS to sites that are not vehicularly navigable and small sites that do not warrant the high deployment costs of a towed array.

3.0 TECHNOLOGY

3.1 TECHNOLOGY DESCRIPTION

3.1.1 Overview

MSEMS is a man-portable evolution of the interleaving electronics in VSEMS, which was a concurrent mag/EM61 system funded under ESTCP Project MM-0208. The VSEMS' interleaving electronics were too big, bulky, and power-hungry for a man-portable application and had interface requirements that were specific to the vehicular configuration. These electronics were redesigned for MSEMS. The primary goals for the MSEMS project were:

- To design and build hardware that would enable the use of a COTS Geonics EM61 Mk2 and a COTS Geometrics total field magnetometer for concurrent operation in a man-portable configuration
- To build an MPI box with standard interfaces that allows use of existing sensors and cables already in inventory and a form factor that allows easy integration with the other COTS EM61 equipment
- To build a system using this new hardware in order to perform the required ESTCP demonstrations.

The resulting system mounts on a COTS EM61 system with its native backpack, coil, and wheels; concurrently collects magnetometer and EM61 data; and is operable by a single person.

3.1.2 Theory of Operation

Historically, simultaneous deployment of magnetometers and the EM61 on a common platform has not been possible because the EM transmission pulse is asynchronous with the magnetometer sampling and thus is picked up by the magnetometers as noise. Even at 10 ft—a practical separation distance for sensor colocation on a common towed platform—EM61-induced noise is over 100 nanotesla (nT), rendering concurrently collected magnetometer data useless.

Under project MM-0208, GEO-CENTERS (now part of SAIC) developed hardware that monitors the pulse from the EM61, waits a preset amount of time for the pulse and the secondary fields generated by the pulse to ring down, then samples the magnetometer for a short window. The magnetometer period counter (MPC) board is designed to interleave the magnetometer and EM61 data acquisition cycles as follows. The MPC circuitry looks for the 1 pulse per second (pps) from the GPS, and then looks for the rising edge of the next EM61 transmission pulse. The system timing then uses a programmable waiting period and a sampling period. The 75 Hz EM61 transmission pulse comes in every 13.3 millisecond (ms). The board waits 8 ms, at which point the EM61 transmission pulse has died off (this has been verified by direct measurement). The MPC board then samples the magnetometers for 5 ms, during the period in which the EM61s are not transmitting. In this way, the magnetometers are sampled only when the EM61s are quiet. This interleaving approach has been successfully used on VSEMS for the past 6 years.

However, on VSEMS, the magnetometers are 8.5 ft from the EM61 array. This is too far for effective configuration on a man-portable platform. In developing a man-portable version of the

interleaving technology for this project (MM-0414), a trade-off study was first conducted to determine how close the magnetometer could be placed with respect to the EM61 coil and still collect high-quality data. The goal was to put the magnetometer as close as possible to the EM61 coil to maximize the benefits of sensor colocation and minimize the complications in positioning that may result from having sensors cantilevered out in front of the GPS antenna. It was determined that, using an unmodified EM61 pulsing at 75 Hz with a 25% duty cycle creating a 3.3 ms square wave pulse, the magnetometer could be placed somewhere in the 3- to 4-ft range from the edge of the EM61 coil and still collect viable data. In order to put the "mag in the middle," it was determined in the trade-off study that the EM61 needed to be slowed from a 75-Hz pulse rate to a 15-Hz pulse rate while maintaining a 3.3-ms pulse width. This is accomplished using an erasable programmable read-only memory (EPROM) chip supplied by Geonics. Changing the chip is a simple five-minute operation that requires opening the EM61 box.

3.1.3 Schematics and Layout

As deployed at YPG, the MSEMS system consists of six basic subsystems:

- **A COTS Geonics EM61 Mk2 backpack system** with EM61 Mk2 electronics box, backpack, battery, cables, coil, wheels, handle, and Allegro hardened personal digital assistant (PDA) and its mount
- **A COTS Geometrics 822A** cesium vapor total field magnetometer with sensor bottle, sensor head, cable, and battery pack
- **A COTS GPS** (on loan from SAIC—not strictly part of the project)
- **The MPI box** and related cabling
- **The magnetometer mount** (mag-in-the-middle and mag-in-front versions)
- **The custom MSEMS data acquisition software** that runs on the Allegro

The layout, showing the major subsystems, is pictured in Figures 1 and 2. The same basic interleaving design was employed as was used for VSEMS in Project MM-0208, but the interleaving electronics and the related data acquisition system were all redesigned and made smaller, lighter, and less power hungry. The resulting MPI box has the same physical form factor as an EM61 box, utilizing the same enclosure used by Geonics to house their EM61 electronics. This design allows the MPI box to mount on the backpack, on top of the EM61 box, using the same set of through holes. The MPI box can accept up to two magnetometers and up to two EM61s, but it is configured for use in MSEMS with a single magnetometer and a single EM61. The MPI box weighs about 2 lb.

Figure 1 shows the backpack fully populated with EM61 battery, the GPS, and all related cabling. The GPS shown is not technically part of MSEMS—it is a GPS of opportunity, SAIC's Trimble 5700 with integral batteries and radio, supplied to the project at no cost under the Cooperative Research and Development Agreement (CRADA) SAIC has with CEHNC. It is mounted to the backpack, on top of the EM61 battery, by a Velcro strap, using a right-angle bracket so it doesn't slide off the battery. This allows the GPS to be quickly removed so the EM61 battery can be changed. Ideally, an all-in-one GPS receiver such as the Trimble 5800 where the antenna, receiver, and radio are all part of a single unit would be used. Note that

subsequent incremental improvements to MSEMS include the use of a Geonics EM61 Mk2A, where the backpack is completely eliminated and both the Geonics electronics and the MPI box are mounted on the handle. We will discuss this configuration—which was not directly funded by this project—near the end of this report. But the fact that the MPI box can be used in either an Mk2 (backpack) or Mk2A (no backpack) configuration, as well as in vehicular and marine applications, attests to the flexibility of the design.

Figure 1. Close-Ups of EM61 Backpack with EM61 Electronics Box, EM61 Battery, MPI Box, and GPS.

The GPS is strapped to the backpack with a velcro strap, and has a right-angle bracket so it won't slide off the battery. Subsequent development has relocated this GPS onto the handle, or utilized a GPS with the receiver and antenna all in a single tripod-mounted package.

A COTS Geometrics battery belt pack powered the magnetometer and the MPI box. The battery belt pack was worn around the waist. Field testing revealed this to be a lot of weight on the operator, and uncomfortable due to close proximity to the EM61 backpack's waist strap, so in later deployments a hardened case was procured to hold the magnetometer batteries and was mounted on the boom. This had the additional benefit of providing a better distribution of weight. The EM61 battery on the backpack powers its native EM61 hardware. The GPS is powered by its own internal batteries.

Figure 2 shows MSEMS at YPG, with the operator wearing the backpack and magnetometer battery belt pack, and pushing the EM61 platform with the magnetometer mounted on a boom 4 ft in front of the EM61 coil, and hosted at a constant height above ground by a third EM61 wheel. After the YPG demonstration, the system was improved in many ways, and now has the configuration shown in the figure on the cover page of this report.

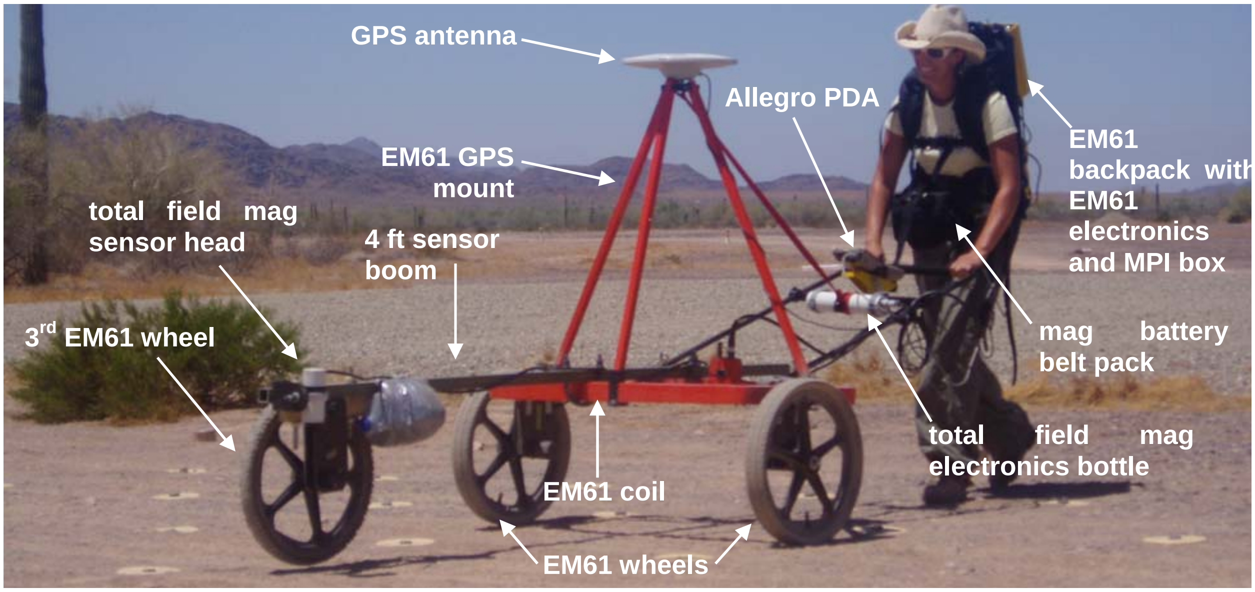

Figure 2. MSEMS at YPG Configured with the Magnetometer 4 ft in Front of the EM61 Coil.

The Allegro is an environmentally hardened PDA that comes as part of the full-up EM61 Mk2 system. We are using it to host our custom data acquisition software. Rather than having the EM61 connected to the Allegro, however, the EM61, magnetometer, and GPS are all connected to our MPI box, and the MPI box is connected to the Allegro. This allows the Allegro, running our own custom software, to collect all geophysical data.

The magnetometer is held in a custom pivoting mount. This mount enables the magnetometer to be optimally oriented with respect to the Earth's magnetic field, then easily swung around to face the other way at the start of the next survey line (in practice, this has not been necessary). The mount is hosted by the EM61 coil and wheels, mounted either in the middle of the coil or 4 ft in front of the coil.

3.1.4 Chronological Summary

- Fall 2002 – First demonstration of interleaving technology on vehicular platform (MM-0414)
- Spring 2004 – Tradeoff study using heavy vehicular electronics, showing that a total field magnetometer can operate 3 to 4 ft from an unmodified EM61
- Fall 2004 – Development of tethered mockup showing the promise of mag-in-the-middle operation if EM61 is slowed down from 75 Hz to 15 Hz
- Spring 2005 – Development of untethered mockup, and design and development of new interleaving hardware
- Fall 2005 – Delivery of new interleaving hardware, development of MPI box, integration and testing, and development of MSEMS system
- Spring 2006 – Test surveys of MSEMS system
- June 2006 – Deployment of MSEMS to YPG.

3.1.5 Summary of Development

Data from a tethered mockup constructed for the tradeoff study, using interleaving hardware from the vehicular VSEMS system, showed that a magnetometer could be operated 3 to 4 ft in front of the coil, or in the middle of the coil if the EM61 were slowed down from 75 Hz to 15 Hz. These data were presented in detail to ESTCP at the October 6, 2004, Interim Program Review (IPR). Data acquired with an untethered mockup over a 25-ft plot were presented at the May 4, 2005, IPR. On the basis of these data, the basic design for MSEMS and for the MPI box was codified. The MPI box was built, tested, and debugged. Although the design of the basic interleaving circuitry from the VSEMS electronics was heavily leveraged, MSEMS' testing and integration took longer than anticipated due to changes necessary to support new software tools needed to program the application-specific integrated circuit (ASIC) chip used to control the timing. The electronics hardware was then packaged into an EM61 enclosure to allow easy physical mounting on top of the EM61 electronics box. Testing and integration was performed at sites of opportunity near Newton, Massachusetts, prior to deployment at YPG.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The complementary nature of the weaknesses of the sensors described above is one of the very things driving their concurrent use in MSEMS. The overriding advantage of the technology is the ability to collect *concurrently* magnetometer and EM61 data in a single survey pass and thus compensate for each other's shortcomings. Separate man-portable magnetometer and EM61 surveys can be contracted through many geophysical houses, but MSEMS is unique in its ability to collect data concurrently from these two industry-standard sensors in a man-portable configuration. Our experience with VSEMS has been that, on site after site, project managers are surprised by the MEC population and geology, and the use of both sensors puts them in the best position to deal with the unexpected. Further, the data from MSEMS, because they are acquired on a common rigid sensor platform, are spatially coregistered, whereas data acquired in separate survey passes may not traverse the same objects in the same way, which may limit the efficacy of the data for discrimination algorithms.

There are several other competing technologies for concurrent magnetometry and EM, but as of this date, none use a COTS industry-standard EM61.

The main limitation of the core interleaving technology is that it applies only to pulsed induction EM systems; it is not applicable to frequency-domain EM systems. For the magnetometer, the technology is currently limited to cesium vapor magnetometers outputting a Larmor signal. It cannot, as presently configured, be used with less expensive fluxgate magnetometers. This is because the interleaving hardware is expecting a Larmor signal as input; it performs period counting of the Larmor signal between EM61 pulses to convert the frequency-based Larmor signal into nT. A fluxgate magnetometer does not employ the resonance mechanism of an alkali vapor magnetometer and as such does not output a frequency-based Larmor signal.

A minor limitation is the way that heading is currently handled. On a COTS EM61, the GPS antenna is configured on a tripod directly over the sensor. Thus, an EM61 can be turned around quickly at the end of a survey line and positioned for the next line without engendering any heading error because there is no moment arm in the geodetic calculation separating the sensor from the GPS antenna. Because MSEMS utilizes two sensors, however, the GPS antenna can't

be over both sensors. If the GPS antenna is configured over the EM61 coil (as it was at YPG), then it is over 4 ft from the magnetometer sensor head. Heading is calculated in post-processing by using adjacent GPS updates and by making assumptions about smooth motion (requiring that the sensor head align itself along the GPS track). This works fine except when the handle is pushed down, the front wheel is lifted up, and the system is swung around quickly on the back wheels. As such, on survey grids, the system is best operated by pausing data acquisition at the end of each line, and carefully positioning it at the beginning of the next line before restarting data acquisition. This takes less than ten seconds for a trained operator to do and does not represent a major limitation. In eventual releases of the system we may consider the addition of a compass to directly measure fast-changing heading instead of inferring it from GPS location and smooth operation.

4.0 PERFORMANCE OBJECTIVES

The stated heuristic objectives of the demonstration as listed in the YPG Demonstration Plan were:

- To test the new prototype MSEMS hardware, software, and platform in a controlled environment, and demonstrate that the MSEMS can withstand the rigors of real deployment
- To acquire magnetometer-only survey data as a baseline to compare with the concurrent EM and magnetometer survey data
- To acquire EM-only survey data as a baseline to compare with the concurrent EM and magnetometer survey data
- To acquire concurrent magnetometer and EM survey data from each of two configurations in order to judge the quality of the data and the efficacy of the system design. The two configurations are:
    - Sensors physically separated by roughly 4 ft using an unmodified EM61 operating at 75 Hz
    - Sensors spatially colocated with the magnetometer in the middle of the EM61 coil, and the EM61 slowed down to 15 Hz.

These heuristic objectives result in the formal performance objectives in the table below.

Table 1. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Qualitative	Reliability and robustness	General observations	Yes
	System usability	General observations	Yes
Quantitative	Concurrent magnetometer data quality	Signal and noise similar to magnetometer-only data	Yes
	Concurrent EM61 data quality	Signal and noise similar to EM61-only data	Yes
	15 Hz mag in the middle magnetometer data quality	signal and noise similar to 75 Hz data	Yes
	15 Hz mag in the middle EM61 data quality	Signal and noise similar to 75 Hz data	No

The metrics for judging similarity of signal and noise of concurrently-collected data to single-sensor data are a visual comparison of image and waveform data over background and over targets, and measured values for signal and noise, again, over background and over targets.

All the heuristic objectives were met—we ran the system in both mag-in-front and mag-in-the-middle modes and made a clear determination of the usefulness of both configurations as follows:

- The system functioned well with only minor cabling and software glitches, to be expected of prototype hardware deployment.
- The 75 Hz mag-in-front configuration collected high-quality concurrent magnetometer and EM61 data, with no discernible difference between singularly acquired data and concurrently acquired data.
- The 75 Hz mag-in-front configuration, with its “cart” design and third wheel, proved to be quite usable (the deployment produced a list of desired incremental improvements, all of which have since been made).
- The magnetometer can be left vertical when using the 75 Hz mag-in-front configuration, simplifying deployment logistics.
- The 15 Hz mag-in-the-middle configuration functioned as designed, collecting high-quality magnetometer data when the magnetometer was properly oriented for each survey line.
- There was no discernible difference between single-sensor magnetometer data and concurrently acquired magnetometer data.

However, the loss in EM61 signal when operating at 15 Hz as compared to 75 Hz that was first seen in the parking lot test is very real, making the “mag-in-the-middle” configuration of questionable use for real-world DGM.

5.0 SITE DESCRIPTION

The demonstration was conducted at the Standardized Unexploded Ordnance (UXO) Demonstration Test Site in Yuma, Arizona. This site was selected as the initial test site because of a planned deployment of the vehicular VSEMS to YPG and the opportunity for MSEMS to be demonstrated at the same time by personnel already on the site.

5.1 SITE LOCATION AND HISTORY

The Aberdeen Proving Grounds (APG), Maryland, and YPG sites were established in 1999 to provide a standard demonstration area for emerging MEC detection-related technologies. YPG is adjacent to the Colorado River in the Sonoran Desert. The UXO Standardized Test Site is south of Pole Line Road and east of the Countermine Testing and Training Range. The open field range, calibration grid, blind test grid, mogul area, and desert extreme area comprise the 350 m by 500 m general test site area. The open field site is the largest of the test sites and measures approximately 200 m by 350 m. To the east of the open field range are the calibration and blind test grids that measure 30 m by 40 m and 40 m by 40 m, respectively. South of the open field is the 135 m by 80 m mogul area consisting of a sequence of man-made depressions. The desert extreme area is located southeast of the open field site and has dimensions of 50 m by 100 m.

5.2 SITE GEOLOGY

Through prior fieldings at YPG, we know that the soil and rocks are somewhat ferrous, causing relatively minor noise on the magnetometers. The geology has been comparatively inert to the EM61s.

5.3 MUNITIONS CONTAMINATION

We surveyed the calibration grid and the blind test grid. The calibration test grid contains clutter items, steel spheres, loops of wire, and 20 mm, 40 mm, M42, BLU-26, BDU-28, 57 mm M86, MK 118, 60 mm, 81 mm, 2.75 in, 105 mm, and 155 mm ordnance items. The blind grid contains the same mix of items. A map of the YPG site is shown in Figure 3.

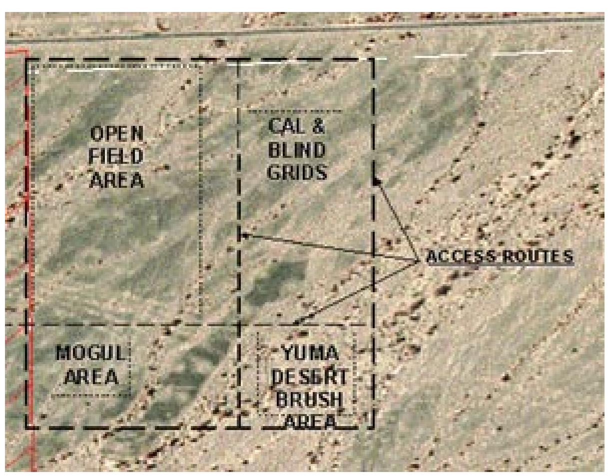

Figure 3. Standardized UXO Demonstration Test Site at Yuma, Arizona.

6.0 TEST DESIGN

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

MSEMS was deployed and tested at YPG to provide general equipment shakedown to verify that the new version of concurrent mag/EM hardware (previously validated under MM-0208) worked as designed and to evaluate the performance and deployment trade-offs of the two physical configurations (75 Hz mag-in-front and 15 Hz mag-in-the-middle).

6.2 SITE PREPARATION

Not applicable.

6.3 SYSTEM SPECIFICATION

6.3.1 Operating Parameters for the Technology

As said above, the tradeoff study conducted at the beginning of the project showed that the magnetometer can acquire high-quality interleaved data when it is 3 to 4 ft from an EM61 coil running at 75 Hz, and also showed the promise of successfully acquiring interleaved data with the magnetometer in the middle of the EM61 coil if the EM61 pulse repetition rate is slowed down from 75 Hz to 15 Hz. These two configurations are summarized in the table below. It should be remembered that, throughout this document, when we say "75 Hz data," the magnetometer is always 4 ft in front of the EM61 coil, and when we say "15 Hz data," the magnetometer is always in the middle of the EM61 coil.

Table 2. Magnetometer Sampling Parameters for the Two Coil-to-Magnetometer Sensor Spacings

Magnetometer Location	EM61 Pulse Rate	Wait	Sample
4 feet outside EM61 coil	75 Hz (unmodified)	8 ms	5 ms
In the middle of EM61 coil	15 Hz (modified with EPROM)	60 ms	5 ms

6.3.1.1 <u>Magnetometer</u>

MSEMS collects total field magnetometer data, triggered primarily by the 1 pps signal from the GPS, and secondarily by the Synchronization Pulse (PSYNC) signal from the EM61 Mk2, for a short window after the secondary field has rung down and before the next PSYNC signal indicating the start of a new EM pulse. For an unmodified EM61, PSYNC is a 75 Hz signal, creating a 13.3 ms cycle. We wait for 8 ms and then sample for 5 ms. This sampling window is repeated at 75 Hz. During the trade-off study, we varied the waiting time and the sampling time, and found this to be the best trade-off. For mag-in-the-middle operation, the EM61 is run at 15 Hz, creating a 66.6 ms cycle. Here, we wait for 60 ms and then sample for 5 ms. Triggering the MPC with the GPS' 1pps creates magnetometer data that is always correctly synchronized with the GPS data and requires no latency correction. Magnetometer height is 30.4 cm (12 in)—slightly below the height of the EM61.

6.3.1.2 EM61

MSEMS collects EM61 Mk2 data, clocked by the EM61's internal PSYNC square wave. An unmodified EM61 internally pulses at 75 Hz. We employ this configuration when the magnetometer is 1.22 m (4 ft) in front of the EM61 coil. For mag-in-the-middle operation, the EM61's EPROM was replaced with one from Geonics that runs the system at 15 Hz rather than 75 Hz. Like the 75 Hz EPROM, the 15 Hz EPROM holds the PSYNC square wave high for 3.3 ms.

Note that with the EM61, there is a distinction between the internal pulse repetition rate and the rate at which it outputs the serial data updates. The EM61 will spit out an output to the recording computer when it is sent a triggering byte that is generated by the data acquisition software. We nominally send this triggering byte at 10 Hz. We always believed that the EM61 "stacks" (averages) data between triggers, so at its 75 Hz internal pulse repetition rate, we expected the EM61 to be averaging five times more readings when it generates an output than when it is at 15 Hz. We expected to see some effect of the inverse root N dependency when we compared EM61 data taken at the 15 Hz pulse repetition rate to data taken at 75 Hz. However, after the YPG deployment, upon speaking with Geonics, we learned that the "stacking" belief turned out to be fallacious; see the data interpretation section below.

EM61 sensor standoff is unchanged from the COTS configuration of 42 cm. Although the system is capable of using an EM61 upper coil and employing the "D" setting on the electronics, we typically do not deploy the upper coil but instead deploy only the lower coil and employ the "4" setting on the electronics box. This uses time-gates sampled at 256, 406, 706, and 1306 μs (microseconds), respectively. The EM61 batteries are expected to last 3-4 hours, and thus are expected to be changed once or twice daily.

6.3.1.3 RTK GPS

Purchase of positioning equipment was not part of the MSEMS project; MSEMS was demonstrated at YPG using differential GPS real-time kinematic (RTK) equipment on loan from SAIC under a CRADA with CEHNC. This equipment consists of a Trimble MS750 base station, Trimble TrimMark III base radio, and a Trimble 5700 rover receiver with integral radio and batteries. We recorded GPS data at 1 Hz. Note that while MSEMS will function with any GPS offering a 1 pps output and a standard ASCII position string output, the selection and placement of any GPS equipment must be accompanied by noise and signature testing to see what static, directional, and time-varying effects the equipment has on both the magnetometer and the EM61 data. Trade-offs typically need to be made between placing the antenna near the sensor (which increases both positional accuracy and signature) and high above the sensor (which decreases both positional accuracy and signature). In keeping with the design philosophy of allowing contractors to use equipment already in inventory, an integrated all-in-one receiver such as the Trimble 5800 would be used instead of a separate receiver/antenna configuration, as this receiver has the electronics, batteries, and antenna all housed in a single unit that can be mounted on the tripod, keeping additional electronics, cabling, and weight off the backpack. Commercial contractors frequently deploy these integrated units via a tripod supplied directly by Geonics that holds the unit 1 m above the coil. Whether this is a low-noise configuration would need to be verified by direct signature and noise evaluation.

6.4 DATA COLLECTION

6.4.1 Scale

The scale of the test was relatively small, utilizing the 40 m x 30 m calibration grid and the 40 m x 40 m blind grid.

6.4.2 Sample Density

The 1 m x ½ m EM61 coil is located with the 1 m axis cross-track. We ran the traverses down the center of the lanes in the calibration and blind grids, with extra traverses on the lane markers themselves, yielding an 0.5 m lane spacing. Traverses were run North-South.

The down-track spacing is a function of sampling rate and speed and is effectively a function of the EM61's output rate, since it is much slower than the magnetometer's output rate. The EM61 outputs at 10 Hz. In order to achieve a nominal down-track data spacing of one EM61 update per 10 cm, the speed needs to be no greater than 1 m/sec, or 2.23 mph. This was the planned speed for the YPG surveys. As we will describe below, we also surveyed at an exaggerated slow speed of approximately 0.3 m/sec, which yields a down-track data spacing of 3 cm.

6.4.3 Quality Checks

Data quality checks included a five-minute warm-up period, a transient object response test (placing and then removing a metallic object), and in-field processing by the principal investigator (PI).

6.4.4 Data Summary

For the calibration grid, we acquired concurrent mag/EM data at 75 Hz with the mag remaining vertical, concurrent mag/EM data at 75 Hz optimally tilting the mag at the start of each survey line, and single sensor mag and EM data at 75 Hz. We acquired similar data at 15 Hz, except that the tilt/no-tilt test was not performed because it was already known that, with the magnetometer in the middle of the EM61 coil, it had to be optimally tilted. An extra set of slow-walked data, both mag-alone and concurrent mag/EM, was acquired at 15 Hz. This yielded the following set of data files for the calibration grid:

- 75 Hz mag-in-front, EM only
- 75 Hz mag-in-front, mag only
- 75 Hz mag-in-front, concurrent mag/EM, magnetometer vertical
- 75 Hz mag-in-front, concurrent mag/EM, magnetometer tilted
- 15 Hz mag-in-the-middle, EM only
- 15 Hz mag-in-the-middle, mag only
- 15 Hz mag-in-the-middle, concurrent mag/EM, magnetometer tilted
- 15 Hz mag-in-the-middle, EM only, slow-walked
- 15 Hz mag-in-the-middle, concurrent mag/EM, magnetometer tilted, slow-walked.

The blind grid matrix was similar to the calibration grid matrix, except that, on the basis of the calibration grid data, we left the mag vertical for the 75 Hz test. This resulted in the following set of files for the blind grid:

- 75 Hz mag-in-front, EM only
- 75 Hz mag-in-front, mag only
- 75 Hz mag-in-front, concurrent mag/EM, magnetometer vertical
- 15 Hz mag-in-the-middle, EM only
- 15 Hz mag-in-the-middle, mag only
- 15 Hz mag-in-the-middle, concurrent mag/EM, magnetometer tilted
- 15 Hz mag-in-the-middle, EM only, slow-walked
- 15 Hz mag-in-the-middle, concurrent mag/EM, magnetometer tilted, slow-walked.

These data reside at SAIC in Newton, Massachusetts, on the server, in an ASCII comma-delimited format (easting, northing, sensor_number, line_number, time, value [value2, value3, value4]) format. Magnetometer data has a single value in nT. EM61 data has the four time-gate values in millivolts (mV).

6.5 VALIDATION

No digging was performed on this project.

7.0 DATA ANALYSIS AND PRODUCTS

Data processing was geared toward producing geodetically-registered data files that could be read into Geosoft Oasis Montaj and gridded.

7.1 PREPROCESSING

The data were:

- Navigation-corrected using our own Linux-based software to remove spurious jumps that occur when the GPS fix quality does not have a value of 3 (which indicates a cm-level RTK fix). The heading of the cart is calculated at the same time.
- Geolocated using the time of each sensor's update, the time of the closest pair of GPS updates, the heading of the cart, and the GPS antenna-to-sensor offset.

Magnetometer data were:

- Median-filtered (de-spiked) to remove spurious values
- Notch-filtered to remove 60 Hz-induced noise subsampled with the 75 Hz sampling rate
- Reference-corrected to remove diurnal drift.

And EM61 data were:

- Lag-corrected using an empirically determined time shift to align parts of anomalies acquired in separate directions
- Background-leveled using a median filter to dynamically determine background before subtracting it off.

7.2 TARGET SELECTION FOR DETECTION

Target selection for detection was not performed. As per the previously submitted YPG report, analysis centered on signal and noise comparisons between concurrent operating and separately operating configurations, and between 75 Hz and 15 Hz configurations.

7.3 PARAMETER ESTIMATES

Not applicable.

7.4 CLASSIFIER AND TRAINING

Not applicable.

7.5 DATA PRODUCTS

ASCII comma-delimited files as described in section 5.5.4 were produced. These files were imported into Geosoft Oasis Montaj, and gridded data and maps were produced.

8.0 PERFORMANCE ASSESSMENT

8.1 SUMMARY

With the magnetometer 4 ft in front of the EM61 coil and the EM61 not modified in any way, the system performs like the previously validated VSEMS vehicular system: it concurrently collects high-quality EM61 Mk2 and magnetometer data. In this mag-in-front configuration, MSEMS is a useful system that has since gone on to perform numerous surveys.

With the magnetometer in the center of the EM61 coil and the EM61 modified to pulse not at 75 Hz but at 15 Hz to allow the magnetometer sufficient time to acquire data before the next pulse, the quality of the magnetometer data appeared nominal; however the quality of the EM61 data was substantially compromised as compared with data from the unmodified EM61, with signal-to-noise reduced by approximately a factor of seven. This “mag-in-the-middle” configuration was not pursued further.

8.2 PERFORMANCE CRITERIA

Performance criteria are listed the table below.

Table 3. Performance Criteria.

Performance Criteria	Description	Primary or Secondary
Concurrent magnetometer data quality (75 Hz)	Signal and noise in magnetometer data compared to stand-alone mag data	Primary
Concurrent EM61 data quality (75 Hz)	Signal and noise in EM61 data compared to stand-alone EM61 data	Primary
15 Hz mag-in-the-middle magnetometer data quality	Signal and noise similar to 75 Hz mag data	Primary
15 Hz mag-in-the-middle EM61 data quality	Signal and noise similar to 75 Hz mag data	Primary
Reliability and robustness	Downtime due to system problems	Secondary
System usability	General ease of use of MSEMS, including custom hardware and data acquisition software	Secondary

8.3 PERFORMANCE CONFIRMATION METHODS

Concurrent mag/EM61 data were acquired at the nominal 75 Hz rate (that is, with the EM61 internal pulse repetition rate unchanged from its COTS 75 Hz setting and the magnetometer 4 ft in front of the EM61 coil). These data were examined in Geosoft Oasis Montaj to determine signal and noise levels. This examination occurred both heuristically (visually examining the image and waveform data) as well as analytically (building tables of noise and signal over background and targets). These noise and signal levels were compared to those with MSEMS data acquired with the sensors operating individually (that is, data that has no possibility of noise from sensor interference). On the calibration grid, noise levels were benchmarked using a static section of data at the start of the first line. Several representative objects were selected to compare signal. The EM61’s EPROM was then replaced with an EPROM that allowed the

system to run at 15 Hz instead of at 75 Hz; the magnetometer was moved to the center of the EM61 coil; and additional EM61 and magnetometer data were acquired. These data were compared to the 75 Hz data in a similar way, except that the noise confirmation method had to be changed from a static measurement to a dynamic measurement over areas in the grid where there were no emplaced objects.

The conclusions, summarized in the table below, are that:

- With the magnetometer 4 ft in front of the EM coil, concurrent magnetometer/EM data were very similar to the single-sensor magnetometer and EM data for that configuration, validating (as was validated with VSEMS) that there is no apparent loss in magnetometer or EM61 data quality from concurrent sensor operation.
- However, when changing to the mag-in-the-middle configuration and reducing the EM's pulse repetition rate from 75 Hz to 15 Hz, the EM61 data suffers a substantial decrease in signal as well as a substantial increase in noise that effectively rules this configuration out for production geophysics.

Note that the "signal within 15%" metric has nothing to do with concurrent mag/EM and is simply a reasonable expectation of repeatability given variations in test track traversal.

Table 4. Detailed Performance Criteria.

Performance Criteria	Expected Performance Metric (pre demo)	Performance Confirmation Method	Actual (post demo)
PRIMARY CRITERIA (Performance Objectives)			
Concurrent magnetometer data quality (75 Hz)	Noise within 1 nT of stand-alone mag data Signal within 15%	Compare idle noise at the start of survey line in concurrent magnetometer data to that in standalone mag data. Compare signal over selected objects.	Noise difference very small (within 0.2 nT) Signal difference < 11%
Concurrent EM61 data quality (75 Hz)	Noise within 1 mV of stand-alone EM61 data Signal within 15%	Same as above	Noise difference very small (within 0.1 mV) Signal difference < 11%
15 Hz mag-in-the-middle magnetometer data quality	Noise within 1 nT of 75 Hz mag data Signal within 15%	Compare noise and signal in 75 Hz mag data to 15 Hz mag data	Noise difference very small (within 0.2 nT) Signal difference < 11%
15 Hz mag-in-the middle EM61 data quality	Noise within 1 mV of 75 Hz EM61 data Signal within 15%	Compare noise and signal in 75 Hz EM61 data to 15 Hz EM61 data	Normalized noise at 15 Hz almost 9mV more than noise at 75 Hz Normalized signal at 15 Hz within about 18% of signal at 75Hz
SECONDARY CRITERIA (Performance Objectives)			
Reliability	< 20% downtime	Measure downtime during surveys	< 20% downtime (one afternoon out of three days)
Ease of use	System is sufficiently usable to complete data acquisition	Discuss with operator after demonstrations	System was usable; completed data acquisition; improvements made post-survey

8.4 DATA ANALYSIS, INTERPRETATION, AND EVALUATION

Images of all acquired data sets were included in the Final Report; only a subset is shown here.

8.4.1 75 Hz Mag-In-Front Data

Both a heuristic analysis (visual image comparison) and a signal-to-noise analysis were presented in detail in the Final Report. The heuristic analysis showed that magnetometer data acquired at 75 Hz concurrently with the EM61 data and with the magnetometer 4 ft in front of the EM61 coil strongly resembled magnetometer data acquired at 75 Hz without the EM61 operating. These are shown in Figure 4. These images indicates that the interleaving hardware is working correctly, allowing the magnetometer to be properly sampled between EM61 pulses.

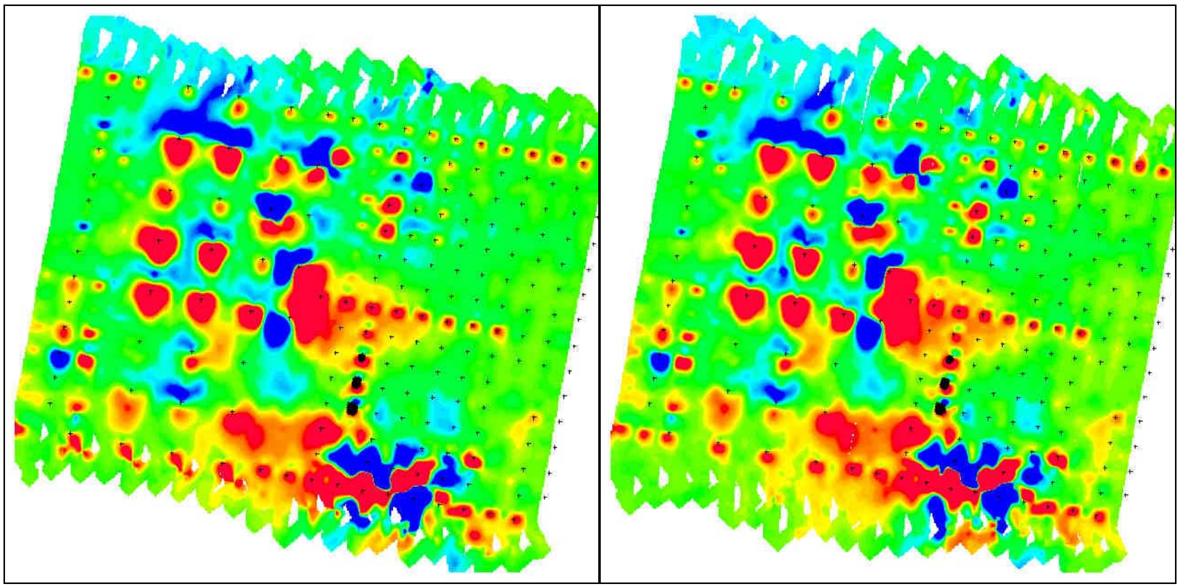

Figure 4. Magnetometer Data (left) and Single-Sensor Magnetometer Data (right) Collected Concurrently from the Calibration Test Grid, Both Collected at 75 Hz with Magnetometer in Front, +- 25 nT.

Similarly, EM61 data acquired at 75 Hz concurrently with the magnetometer data strongly resembled EM61 data acquired at 75 Hz without the magnetometer present, indicating that the physical presence of the magnetometer 4 ft in front of the EM61 coil does not affect data quality. These images are shown in Figure 5.

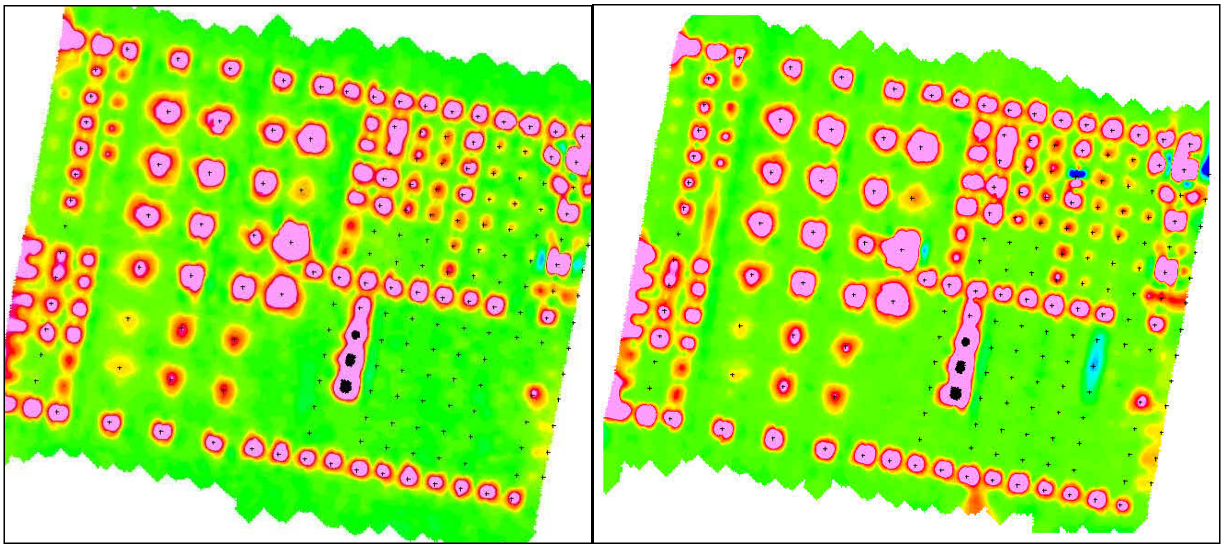

Figure 5. EM61 Gate 1 Data (left) and Single-Sensor EM61 Gate 1 Data (right) Concurrently Collected from the Calibration Test Grid, Both Collected at 75 Hz, +- 25 mV.

In addition to the heuristics in the image data, these conclusions were born out by a signal-to-noise analysis over two objects in the calibration grid, summarized in Tables 5 and 6.

Table 5. Comparison of Magnetometer Signal to Noise for Mag-Only and Concurrent Mag/EM61 Data.

	Noise (nT)	b13 Signal (nT)	b13 s/n	d13 Signal (nT)	d13 s/n
Concurrent mag/EM	0.68	236	347.1	33	48.5
Mag only	0.54	218	403.7	36	66.7

Table 6. Comparison of EM61 Signal to Noise for Mag-Only and Concurrent Mag/EM61 Data.

	Noise (mV)	b13 Signal (mV)	b13 s/n	d13 Signal (mV)	d13 s/n
Concurrent mag/EM	0.4	145.7	364.2	136.8	342.0
EM only	0.4	153.5	383.7	151.9	379.7

8.4.2 15 Hz Mag-In-The-Middle Data

The heuristic analysis showed that the magnetometer data acquired at 15 Hz concurrently with the EM61 data and with the magnetometer in the middle of the EM61 coil strongly visually resembled the stand-alone magnetometer data. This indicates that by slowing the EM61 down from 75 Hz to 15 Hz, the magnetometer can, in fact, operate in the middle of the EM61 coil. The most obvious visual feature in these 15 Hz magnetometer data sets was the presence of down-track streaks in the data indicative of the close proximity of the magnetometer to the nearby electronics. These streaks were present in both the concurrent data as well as the stand-alone

magnetometer data, indicating that they had nothing to do with whether the EM61 was pulsing or not.

Unfortunately, the 15 Hz EM61 data were obviously of lower data quality than the 75 Hz EM61 data, presenting anomalies that were weaker and less well-defined than in the 75 Hz EM61 data. This is clearly shown in Figure 6 below.

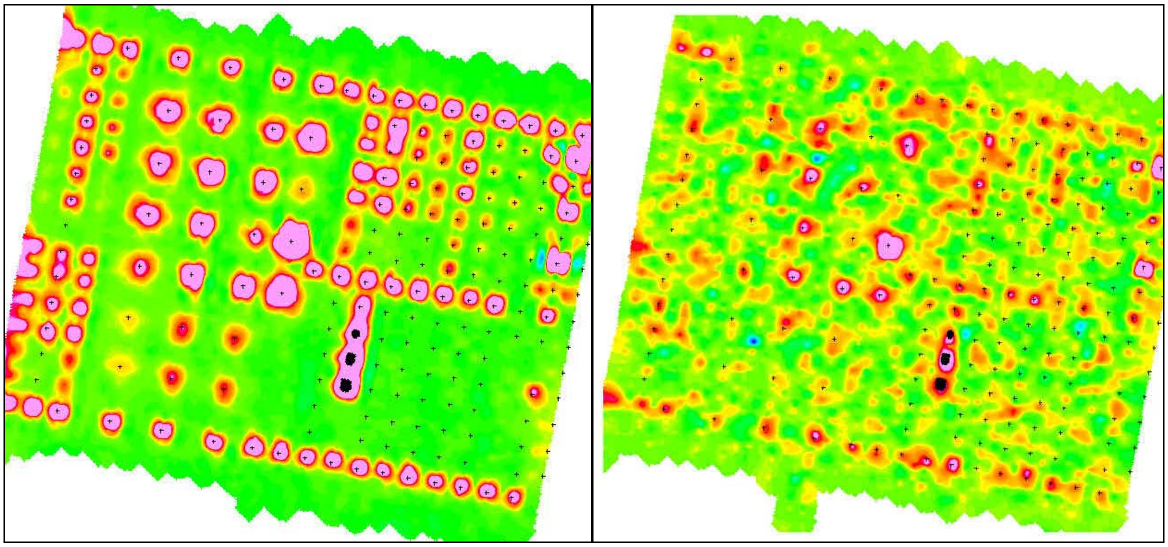

Figure 6. 75 Hz EM61 Gate 1 Data (left) and 15 Hz EM61 Data (right) Collected Concurrently from the Calibration Test Grid, +- 25 mV.

In an attempt to increase signal to noise, we decreased the walking speed from 1 m/sec to 0.3 m/sec, and we requested data from the EM61 at a 2 Hz rate instead of the nominal 10 Hz data output rate. In Figure 7, the anomalies have a tighter, rounder appearance than the 15 Hz data above acquired at a nominal walking speed, but they are clearly degraded as compared to the 75 Hz data above.

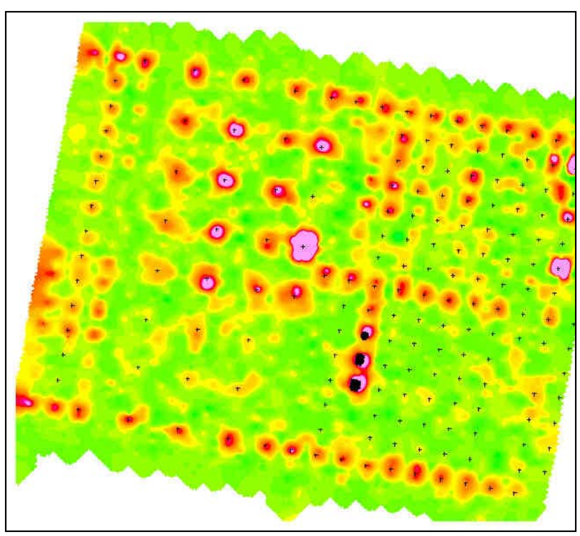

Figure 7. 15 Hz Stand-alone EM61 Data from the Calibration Test Grid, Triggered at 2 Hz and Walked Very Slowly, +- 25 mV.

A signal-to-noise analysis below shows that, even when using data acquired at an unrealistically slow walking pace, a loss of approximately a factor of seven in the signal to noise in the 15 Hz EM61 data compared to the 75 Hz EM61 data.

As originally requested by the Program Office, a signal-to-noise analysis of a line of data in the blind grid is included for completeness. The second line of data in the blind grid appears to run over objects of varying size, so we selected this line for scrutiny. It is instructive to look at these anomalies in time-series form. The top set of profiles (Figure 8) was acquired at normal walking speed at 75 Hz with the magnetometer in front. The middle set of profiles (Figure 9) was acquired at a painfully slow walking pace (approximately 0.3 m/sec) at 15 Hz with the magnetometer in the middle. The bottom set (Figure 10) is the data from the middle set multiplied by a factor of 5, bringing the signal to the same level as the 75 Hz data so the differences in noise can be evaluated. Even though, to the eye, the 15 Hz profiles have the appearance of good data (smooth peaks with quiet valleys), when bringing up the signal and noise by a factor of 5 and comparing apples to apples to the 75 Hz data, the increased noise can clearly be seen. This is especially significant when one considers that the data in Figure 10 took three times as long to acquire than the data in Figure 8, due to the reduced walking pace.

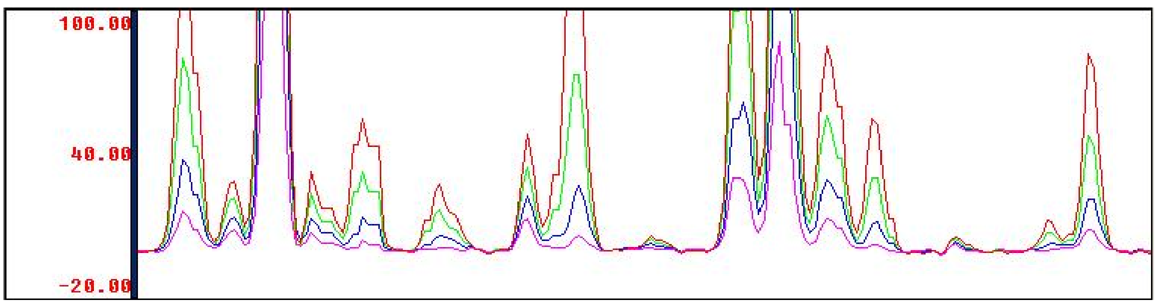

Figure 8. YPG Blind Grid, 75 Hz Mag-in-Front Concurrent EM61 Data, Line 2.

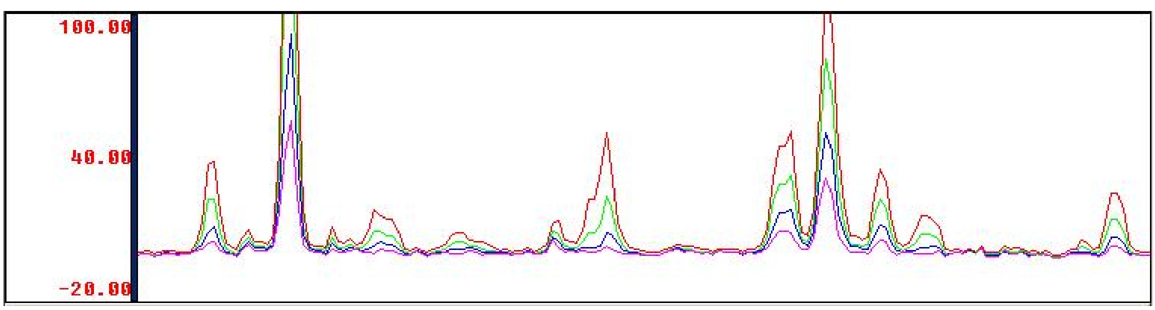

Figure 9. YPG Blind Grid, 15 Hz Mag-in-the-Middle Concurrent EM61 Data, Line 2, Slow Walk.

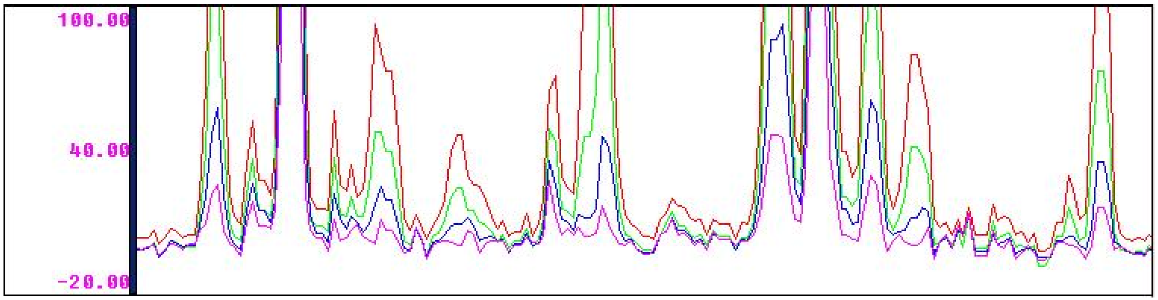

Figure 10. YPG Blind Grid, 15 Hz Mag-in-the-Middle Concurrent EM61 Data, Line 2, Slow Walk, Multiplied by a Factor of 5.

A signal-to-noise analysis has been performed on this line of targets. Table 7 shows data from Gate 1. Noise was measured dynamically using data in an area stretching from grid cell F8 to grid cell K8 where there do not appear to be any emplaced targets. Signal-to-noise values are given for each grid cell in line 2 that contains an object. The last column in the table is the ratio of the signal to noise from the 75 Hz data to that extracted from the 15 Hz data. From here, it is clear that there is a loss of approximately a factor of 6 to 8 in signal to noise when running the EM61 using the 15 Hz pulse repetition rate, even when trying to mitigate the loss in data quality by walking approximately one-third the speed at which the 75 Hz data were collected and decreasing the output rate to 2 Hz.

Table 7. Signal and Noise Analysis of Line 2 in YPG Blind Test Grid.

	0.29 mV		0.61 mV		
Noise	**75 Hz Signal (mV)**	**75 Hz SNR**	**15 Hz Signal (mV)**	**15 Hz SNR**	**Ratio**
b2	70.79	244.10	21.02	34.46	7.08
f2	12.79	44.10	3.62	5.93	7.43
i2	58.71	202.45	19.09	31.30	6.47
m2	20.81	71.76	7.30	11.97	6.00
o2	77.56	267.45	24.70	40.49	6.60
q2	16.56	57.10	5.94	9.74	5.86

SNR – signal-to-noise ratio

8.5 RELIABILITY AND USABILITY

The system proved very reliable at YPG, suffering a broken cable and running the internal GPS battery down once. Total downtime amounted to approximately one afternoon out of a 3-day deployment.

The system operators found the user interface presented by our custom Allegro software to be quite usable (it has a look and feel similar to Geonics' software). Operators liked the third wheel because it enabled them to let go of the handle without having the system fall over (as it does in a COTS two-wheeled EM61). The main operator complaint was that having the EM61 backpack *and* the magnetometer battery belt pack on the operator was too much. The magnetometer batteries were subsequently relocated onto the boom and packaged in a hardened case.

8.6 CONCLUSIONS

At the start of this project, when planning what was necessary to operate a magnetometer in the middle of the EM61 coil, we were primarily concerned about the effect on the magnetometer data quality. We did not expect that the primary degradation in data quality would be not to the magnetometer but to the EM61. When research showed that, by slowing the EM61 down from 75 Hz to 15 Hz, we apparently *could* operate the magnetometer in the center of the coil, we were certainly aware that the EM61 noise would vary as one over the square root of the ratio of the two pulse repetition rates, but we did not know whether this would be a significant source of noise to the system as a whole, much less the most significant source. The YPG deployment showed that the degradation in signal to noise when operating in this mode is crippling to the EM61 data quality. We discussed these results with Miro Bosnar of Geonics. It is possible that further work with Geonics could solve some of the unknowns of our particular one-off 15 Hz EPROM. However, the 75 Hz mag-in-front configuration with the third wheel is a mechanically stable platform that generates high quality EM61 and magnetometer data. For this reason, after the YPG deployment, we have not further pursued the mag-in-the-middle configuration. Further, we have begun using Geonics' COTS EM61 Mk2A as the basis for a newer version of MSEMS (see below). The Mk2A has the battery relocated from the backpack to the center of the EM61 coil. From a purely practical standpoint, it would be difficult to colocate the magnetometer there as well.

The YPG deployment was a crucial shakedown test for MSEMS. It validated the system's ability to collect high-quality concurrent magnetometer and EM61 data at 75 Hz with the magnetometer 4 ft in front of the EM61 coil and supported by a third wheel, and raised sufficient questions about signal to noise in the 15 Hz mag-in-the-middle mode that we elected not to pursue it further at this time. Important bugs were unearthed and fixed, and feedback from experienced operators was obtained. Post-YPG, these issues were addressed, resulting in a string of successful fieldings at a variety of government and commercial MEC HTRW sites.

9.0 COST ASSESSMENT

9.1 COST MODEL

The cost model is presented Table 8.

Table 8. Cost Model.

Cost Element	Data Tracked During Demonstration	Estimated Costs
Instrument cost	Component costs and integration costs: • Engineering estimates based on current development • Lifetime estimate Track consumables and repairs	$25,000
Mobilization and demobilization	Cost to mobilize to site Derived from demonstration costs	$10,800
Site preparation	No unique requirements encountered	
Instrument set-up costs	Unit: $ cost to set up and calibrate Data requirements: • Hours required • Personnel required • Frequency required	$275 1 hour 2 people One-time setup
Survey costs	Unit: $ cost per hectare Data requirements: • Hours per hectare • Personnel required	$2,826/hectare 8.3 hours/hectare 2 people
Detection data processing costs	Unit: $ cost per hectare as function of anomaly density Data requirements: • Time required • Personnel required	No detection performed
Discrimination data processing	Unit: $ per anomaly • Time required • Personnel required	No discrimination performed

Instrument Cost: We estimate the instrument cost of MSEMS as follows. The Geonics EM61, the RTK GPS, and the Geometrics total field magnetometer are COTS equipment used on many DGM surveys that are either purchased and amortized or rented by DGM contractors. This is precisely why the design philosophy of MSEMS was to allow the use of these existing sensors if a contractor already had them in inventory. Approximate costs of these sensors are listed in Table 9. The MSEMS-specific pieces consist of the MPI box and its associated cabling, ancillary EM61 cables and the third EM61 wheel, and the custom magnetometer boom and battery box. We have recently duplicated the MPI box and are attempting to accurately segregate non-recurring engineering (NRE) costs from production costs. The $20,000 to build an MPI box represents an estimate (Table 9), not an actual production cost.

Table 9. Estimated Equipment Cost for MSEMS Hardware.

COTS Equipment	
Geonics EM61 Mk2A	$35,000
RTK GPS	$40,000
Geometrics 822A magnetometer	$25,000
MSEMS-Specific Equipment	
Ancillary EM61 (3rd wheel, sync cable)	$2,000
Custom MPI box and cabling	$20,000
Custom boom and battery box	$3,000
Total	**$125,000**

From this estimate, the cost of the MSEMS-specific pieces is $25,000, or about 20% of the total cost. Note that, under this project, the EM61 and magnetometer were purchased but the RTK GPS was loaned by SAIC.

Mob/Demob: Because MSEMS is man-portable, deployment costs are low; it can be crated and shipped and does not require tractor-trailer transport like a vehicular system. The main components pack into the standard Geonics EM61 silver road cases. A hard ski case has been procured to protect the magnetometer boom. The mob/demob for the two-man crew, including appropriate preparation and packing, is approximately $10,800, which includes $1,000 for shipping.

Site Preparation: No site preparation above that which is necessary for a COTS EM61 is required.

Instrument Set-up Costs: The instrument setup is similar to a COTS EM61, with a few extra boxes and cables. The two-man crew has routinely set the system up and begun collecting data within an hour of arriving at a site. Thus we estimate the cost as an hour of two people.

Survey Costs: The survey costs are similar to those of a COTS EM61, and these, of course, depend on many factors, including site topography, hours of access to the site, weather, and GPS problems. EM61 work is often quoted using a 1- to 2-acre per day coverage rate, depending on the line spacing. Slightly more care must be taken with MSEMS to pause the system at the end of a line and turn it around and orient it properly before beginning to collect additional data. It has been estimated that this takes no more than 10 seconds per line. To calculate an actual per hectare cost based on the YPG demonstration, we multiply the 18 data sets and the size of the blind grid to get a total of 28,800 square meters, or 2.88 hectares (7.1 acres). The length of the survey was 3 days, yielding .96 hectares per day, or about 8.3 hr per hectare using a two-man crew. The rate for the PI and an equipment operator in the field was $2,713/day, yielding $2,826/hectare.

Detection Data Processing Costs: Processing of MSEMS' EM61 data is no different than processing data from a COTS EM61; the data must be de-spiked, lag-corrected, and background-leveled. These steps are performed in Geosoft Oasis Montaj. MSEMS' magnetometer data requires the additional step of notch-filtering out the instrument-specific 15 Hz hum (created by

the 60 Hz ambient electrical hum aliasing at 15 Hz because it is sampled at 75 Hz). We usually perform this step in our own software, but Oasis is capable of notch-filtering the data as well. Because our magnetometer data is 1 pps-triggered, it never requires latency correction. The magnetometer and EM61 data can be read independently into Oasis and independently thresholded to generate a mag dig sheet and an EM61 dig sheet. At present, however, there is not a turnkey method of combining these dig sheets. Different survey jobs have had different requirements. Production surveys have tended to utilize EM61-derived target picks, with any additional unique magnetometer target picks added in by hand. We have recently developed spatial correlation software to read in Oasis-generated mag and EM target databases and output a single database with a column indicating whether each target was detected by the EM61, by the magnetometer, or by both.

Discrimination Data Processing Costs: The scope of this project, to date, has not included discrimination processing.

9.2 COST DRIVERS

In analyzing cost, it cannot be stressed enough that each survey has different requirements, and that these differ from ESTCP's demonstration and validation requirements. Additional work such as geographic information system (GIS), advanced discrimination processing, target relocation, digging, and remediation are not included.

In early surveys using new technology, a primary cost driver is the presence of the senior inventor/engineers on the site. With the vehicular system VSEMS, the inventor's presence is necessary because of the degree of complexity of the equipment. It is expected that, because MSEMS is a simpler system hosted on an EM61 man-portable platform, this will not be as crucial an issue. Because MSEMS is man-portable and uses COTS sensors and because the magnetometer is hosted on the EM61 coil, there is no tow vehicle or towed platform; thus the components can be crated and shipped. We also employ fewer personnel on site than some production geophysical houses. SAIC generally performs surveys using a crew of two expert operators. This is sufficient except when survey traverses are difficult to see due to site size or terrain; in this case, "flaggers" are employed, usually as local temporary labor, to hold flags to help the vehicle operator see his previous traverse. For surveys on active MEC ranges contracted through the Army Corps of Engineers, a higher level of on-site explosive ordnance disposal (EOD) support is mandated, whereas on these demonstration surveys, no EOD support is required.

9.3 COST BENEFIT

The technology unique to project MM-0414 and the prior project MM-0208—interleaving magnetometer data between EM61 pulses, which allows total field magnetometer and EM61 data to be acquired simultaneously—should result in a nearly 50% cost reduction in geophysical data collection efforts as compared to use of magnetometers and EM61s sequentially instead of simultaneously. The question then becomes: When is the use of both sensors strictly necessary, and what is the cost benefit in surveying with both sensors? The Program Office's view has been that a benefit *may* come from the added discrimination information to be gained from the increased data quality derived from having both sensors colocated on a common platform.

Validating this is not part of this or the previous program, and as such the assertion has never been proven either way (though we should find out by deploying MSEMS in the upcoming San Luis Obispo Classification Study). In contrast, the PI's view is that discrimination is not required in order for concurrent mag/EM to be useful. Both VSEMS and MSEMS have been deployed on real sites, and unique detections—anomalies of a size and shape consistent with MEC—have been pulled out of both sensor data sets. On the production surveys, due to a lack of ground truth, we do not have the validation data to prove that these unique detections were in fact MEC. On the research surveys, these data were not submitted for discrimination and classification processing to provide the statistical basis for an MEC or clutter determination.

Viewed narrowly, sites that may require surveys with multiple sensors include sites where the MEC population and/or disposal history is not well known, sites with complex or unexpected geology, or sites where the detection and discrimination requirements are very stringent, such as Camp Sibert or the Former Lowry Bombing and Gunnery Range, where the presence of chemical munitions made the economics of simply digging every item above threshold impossible. Our experience, however, has shown us that nearly *every site* has an MEC population and/or disposal history that is not well known.

10.0 IMPLEMENTATION ISSUES

10.1 ENVIRONMENTAL AND REGULATORY ISSUES

Because the technology involves combining the two sensors most validated against UXO for DGM—total field magnetometers and EM61 pulsed induction coils—there are no specific regulatory issues above those that apply to all DGM data. Any applicable regulatory issues involve detection and discrimination systems of all kinds (i.e., how clean is clean, etc) and are not specific to this project or technology.

10.2 END-USER ISSUES

Because the sensors are not only COTS but the very sensors already well-used for MEC DGM, there should not be serious impediments to use. The design philosophy of MSEMS was to build a box that let us and other DGM contractors plug a COTS EM61 and magnetometer and GPS into it, and we have conformed to that philosophy. We have the added benefit of using the EM61 Mk2, which is a fairly ergonomically well-thought-out system. The fact that MSEMS is hosted on an EM61 makes it look familiar to the user community and should help acceptance. We have tried to disturb it as little as possible, even using the Allegro hardened PDA as the data acquisition computer (running our software instead of Geonics').

10.2.1 Post-YPG System Improvements

Since the YPG demonstration, many incremental improvements have been made to the system. These include:

- Vastly improved error reporting
- Relocation of magnetometer batteries from a hip-worn belt to a hardened pack mounted on the boom
- Relocation of GPS antenna from Geometrics tripod over EM61 coil down onto boom to mitigate positioning error when operating on an incline.
- Being able to pull as well as push MSEMS.

The resulting system, with the battery box and GPS antenna relocated and able to be pulled as well as pushed (Figure 11), was demonstrated at Camp Sibert, Alabama.

Figure 11. MSEMS Cart, with Relocated Battery and GPS, Being Pulled over Rough Terrain at Camp Sibert Site 8.

Incorporation of EM61 Mk2A with No Backpack: Under contract W909MY-08-C-0011, SAIC is developing a Simplified Combined EMI and Magnetometer System (SCEMP) for the Humanitarian Demining (HD) Division of the Night Vision and Electronic Sensors Directorate (NVESD) at Fort Belvoir, Virginia. The goal is to simplify the concurrent mag/EM technology as much as possible for use by a lightly trained deminer for MEC detection in Southeast Asia. The new configuration will include no backpack, unified packaging of electronics boxes, reduced cabling, and a simplified graphical user interface (GUI). Pursuant to those goals, an EM61 Mk2A system was purchased from Geonics. The Mk2A has no backpack; instead, the EM61 electronics box is mounted on the handle, and the EM61 battery is mounted in the center of the coil. As part of early testing of SCEMP, we have combined MSEMS pieces with the EM61 Mk2A. The resulting system (Figure 12) is more comfortable for the operator and has fewer cables.

Figure 12. MSEMS Utilizing an EM61 Mk2A with No Backpack as Part of Testing of a SCEMP for NVESD Division.

Use of a Compact Integrated GPS Without 1 pps Output: Like the previous interleaving hardware developed under MM-0208 (VSEMS), MSEMS' interleaving hardware uses the 1 pps output from a GPS to trigger the magnetometer data acquisition in 1-sec data blocks (the interleaving between EM pulses is conducted within each data block). This method acquires magnetometer data that is always correctly synchronized to GPS and thus requires no latency correction. However, the compact integrated all-in-one GPS units such as the Trimble 5800 favored by geophysical contractors do not have a 1 pps output. Unlike the VSEMS hardware, the newer MSEMS hardware was designed with the capability to function without an external 1 pps and to generate its own internal timing if 1 pps is not available. In order to maximize the ability to allow geophysical contractors to combine an MPI box with equipment they already have in inventory and support these GPS devices, we have modified the firmware in the MPI box to make use of the designed-in capability to function without a 1pps input. Note that, when used in this mode, the benefit of driving the magnetometer data acquisition with 1 pps is lost, resulting in magnetometer data that, like other geophysical data acquired by many COTS systems, may require latency correction.

10.2.2 Subsequent Use of the Technology

Camp Sibert Survey: In May 2007, CEHNC deployed MSEMS to Camp Sibert, Alabama, for further shakedown and testing under the CRADA. MSEMS surveyed the Pineview Circle geophysical prove-out (GPO) plot, and then completed two acres of data acquisition in Site 8. This was a substantially more rugged area than YPG, and was treed.

Camp Howze Survey: In July 2007, CEHNC deployed both MSEMS to Camp Howze, Texas, to survey a set of discrimination grids on a live 60 mm site. A GPO plot and eight 100- x 100-ft grids were surveyed.

Use of the MPI Box to Evaluate Vehicle Magnetic Signatures: During 2006 and 2007, the MPI box was used extensively in support of ESTCP Project MM-0605 (Use of COTS Vehicles for Towed Array Magnetometry). Although MSEMS employs a single magnetometer and EM61, the MPI is capable of hosting two of each sensor. The small form factor of the box enabled us to design an easily transportable electronics package and a small towed platform with two magnetometers and two EM61s, and move the platform and all related electronics quickly and easily between different vehicles used for small area surveys to measure vehicle magnetic signature. The resulting Towed Simultaneous Electromagnetic Induction and Magnetometer System (TSEMS) system may be used for areas too large for MSEMS but too small to justify the deployment costs of the full-sized VSEMS.

Chappaquiddick MEC Survey: In July 2008, MSEMS was employed by CEHNC to survey several miles of beach along Chappaquiddick Island, off Martha's Vineyard, Massachusetts, where several MEC items had been found by bathers. In one survey pass, CEHNC was able to collect both magnetometer and EM61 data to be used to evaluate which sensing technology should be called for in an eventual request for proposal.

Underground Storage Tank Survey: In September 2008, MSEMS was deployed in a commercial survey to detect underground storage tanks at an HTRW site. The site was extremely cluttered, with aboveground storage tanks fed by overhead plumbing. Contrary to the assumption

that the EM61 would outperform the magnetometer in such a cluttered environment, several potential tank targets became apparent once the magnetometer data were reduced to analytic signal in Oasis.

National Association of Ordnance and Explosive Waste (OEW) Contractors (NAOC) Tech Transfer Workshop: The system generated much interest when it was demonstrated at the 2008 NAOC Tech Transfer workshop. Comments were publicly made in the question and answer (Q&A) session at the end of the workshop that, of all the technologies demonstrated, MSEMS was the only one that was field-ready.

Development of Additional MPI Boxes: We have made minor changes in connector placement on the initial MPI box and have updated all documentation to allow the production of additional boxes. The first of these was produced and tested in August 2008. Naeva Geophysics, Parsons, and Weston Geophysics have all expressed serious interest in demonstrating and/or purchasing an MPI box.

Planned Use of an MPI Box in MM-0733: ESTCP Project MM-0733 (Underwater Simultaneous EMI and Magnetometer System [USEMS]) is planning to use an MPI box in a COTS fashion to simultaneously acquire magnetometer and EM61 data from a towfish rigidly attached to the back of a boat. Initial USEMS testing is expected in early 2009.

10.3 RELEVANT PROCUREMENT ISSUES

The EM61, GPS, and magnetometer are COTS, but the MPI box is custom. We have updated the drawing package and are attempting to segregate NRE costs from manufacturing costs in order to develop an accurate cost model for small-scale production.

10.4 AVAILABILITY OF THE TECHNOLOGY

As above, we are on the verge of building more boxes. We plan to put together a kit consisting of the MPI box that performs the interleaving, the custom cabling, and a magnetometer mount, and supply this to CEHNC. If CEHNC regards the kit as viable, we will try to market it to other DGM contractors. As said above, we already have serious interest from three DGM contractors.

10.5 SPECIALIZED SKILLS AND TRAINING

Because the sensors are not only COTS but the very sensors already well-used for MEC DGM, training is minimal. MSEMS has already been operated by field technicians accustomed to operating an EM61 with a few hours of training.

11.0 REFERENCES

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APPENDIX A

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